Electrical Safety 101 for the Laser Safety Officer

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10TH ANNUAL DEPARTMENT OF ENERGY LASER SAFETY OFFICER WORKSHOP

Abstract

- The rules which construct the electrical safety envelope for lasers at DOE facilities will be stated. Then several electrical safety techniques will be shown that apply to commercial and R&D lasers. Examples of how to use grounding, bonding and guarding will be given. Failures of water cooling that may lead to shocks will be detailed. Human response to shock will be discussed.

- Author Biography

- Gary R. Dreifuerst is a retired electronics engineer from Lawrence Livermore National Laboratory (LLNL). He joined LLNL in June 1981 after receiving his EE PhD degree from the University of Wisconsin-Madison.
- He worked in the LLNL Laser programs (Shiva, Novette, Nova, AVLIS, NIF) for 32 years. Gary was the Electrical Safety Officer for the National Ignition Facility and the chair of the LLNL Electrical Safety Committee.

LIA Family of Standards

ANSI Z136 Standards

ANSI Standard	Latest Publication Date	Previous Publication Dates (and Notes)
Z136.1	2014	1973, 1976, 1980, 1986, 1993, 2000, 2007
Z136.2	2012	1977, 1988, 1997
Z136.3	2011	1988, 1996, 2005
Z136.4 (RP)	2010	2005
Z136.5	2009	2000
Z136.6	2005	2000
Z136.7	2008	
Z136.8	2012	
Z136.9	2013	
Z136.10		

Laser Institute of America
Laser Applications and Safety

DOE Rules that affect Lasers

- DOE is mandated by 10CFR851 to follow several standards and laws – GDC already makes this true
  - Under section 5 of the OSH act, there is the "General Duty Clause", which is cited by OSHA to bring in a recognition by a national standard of a risk in the workplace. (Look for "GDC" in the following slides.)
    - Each employer shall furnish to each of his employees employment and a place of employment which are free from recognized hazards that are causing or are likely to cause death or serious physical harm to his employees - 29 USC 654.5
    - OSHA Letter of Interpretation Botts 20061018 – GDC explanation
  - OSHA – 29CFR1910 – this also applies to many businesses in the US, not just DOE
    - Subpart S – defines Electrical Safety for General Industry
    - It defines the meaning of "Acceptable" applying to the three types of evaluations that could be applied to equipment for safety.
      - NRTL examination – 1910.7
      - Local inspection if no NRTL looks at this type of equipment
      - Custom made for one customer with test data to prove it
    - It also defines "Approved" as being acceptable to the AHJ

DOE Rules that affect Lasers

- NFPA 70 – National Electric Code – each state and city may modify this before adopting it. Once adopted, it is law.
  - Defines the AHJ
    - An organization, office, or individual responsible for enforcing the requirements of a code or standard, or for approving equipment, materials, an installation, or a procedure.
    - Unapproved equipment is not allowed to be energized
    - Each DOE facility has an AHJ structure. Some are more extensive than others. **Get to know your AHJ!**
- NFPA 70E - Electrical Safety in the Workplace – optional for many companies, but OSHA will use GDC to bring it into the conversation. **Qualified and Authorized workers only!**
  - Emphasis is on performing all work in a de-energized state
  - Approach distances based on voltage and type of electricity (AC/DC)
    - LAB, RAB, PAB (Limited, Restricted, Prohibited)
  - PPE required for shock (RAB) and Arc Flash protection inside the AFB (> 1.2cal/cm^2 or 5 J/cm^2)

DOE Rules that affect Lasers

- LIA Z136.1
  - Just like for 70E, this will be optional for many companies, but OSHA will use GDC to bring it into the conversation.
  - Laser electrical safety issues are not extensively addressed by the ANSI 136.x family of documents. They fall under the category of "Non-Beam Hazards", Section 7 and Appendix F.
  - LOTO to secure hazardous energy – is mentioned in 136.1-2007,
    - **4.3.4 Key Control (Class 3B or Class 4).**
    - All energy sources associated with Class 3B or Class 4 lasers or laser systems shall be designed to permit lockout/tagout procedures required by the Occupational Safety and Health Administration (OSHA) of the U.S. Department of Labor (see Section 10 for reference).
      - What about the other laser classes?
      - LOTO is key to the structure of 70E

DOE Rules - NRTLs

- Some of the NRTL symbols used

DOE Rules - NRTLs

- Organizations Currently Recognized by OSHA as NRTLs
  - Canadian Standards Association (CSA)
  - Curtis-Straus LLC (CSL)
  - FM Approvals LLC (FM)
  - Intertek Testing Services NA, Inc. (ITSNA)
  - MET Laboratories, Inc. (MET)
  - Nemko-CCL (CCL)
  - NSF International (NSF)
  - QPS Evaluation Services Inc. (QPS)
  - SGS North America, Inc. (SGS)
  - Southwest Research Institute (SWRI)
  - TUV Rheinland of North America, Inc. (TUV)
  - TUV Rheinland PTL, LLC (TUVPTL)
  - TÜV SÜD America, Inc. (TUVAM)
  - TÜV SÜD Product Services GmbH (TUVPSG)
  - Underwriters Laboratories Inc. (UL)

DOE Rules – NRTL – UL’s symbols

- UL Listing Mark
- C - UL Listing Mark
- C - UL - US Listing Mark
- Classification Mark
- C - UL Classification Mark
- C – UL - US Classification Mark
- Recognized Component Mark
- Canadian Recognized Component Mark
- Recognized Component Mark for Canada and US
- Field Evaluated Product Mark

DOE Rules - Not an NRTL – but often seen

CE

Conformite Europeene

- A CE mark is self-certification by the manufacturer, not 3rd party evaluation to a national safety standard. It is a necessary mark for European commerce.
- The product may be very good, but CE is not a US NRTL mark and the AHJ should not accept it without further examination.

Test Yourself – Ebay Product & Nameplate

- Is it a good buy?
- What do these mean?

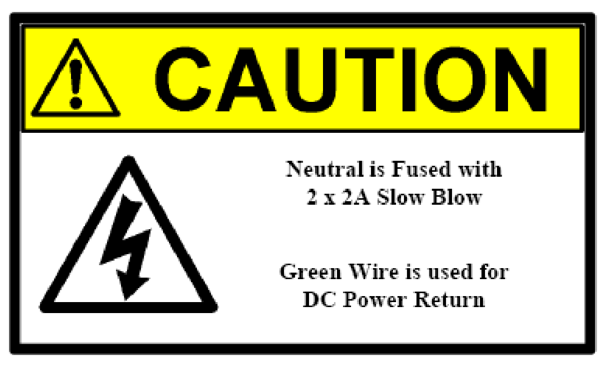
- Recognized Component – UL
- NRTL TUV
- CE - nothing

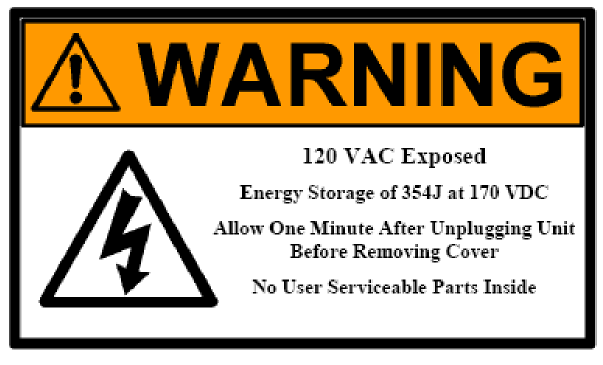
DOE Rules - Enclosures

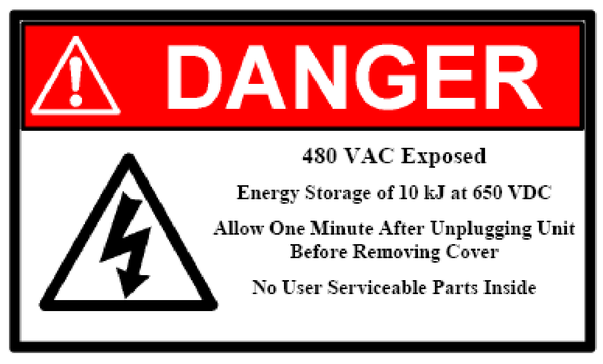
- Enclosures provide electrical protection of the exposed terminals and single-layer insulated wiring.
  - Lasers frequently need to be adjusted while operating and therefore energized. Use metal or di-electric guards (polycarbonate) to protect the worker from those hazards. This makes the task one without possibility of shock exposure.
  - High energy lasers require enclosures to protect from Arc Flash and Blast hazards
    - This may be in the form of entire rooms (capacitor banks)
  - To qualify under OSHA, warning signs must be present and a tool must be used to expose a worker to a hazard.
    - Tool could be a screwdriver to remove a small guard or a key-lock system (Kirk) for access to a enclosure or room

Enclosures need Warning Signs – NEMA Z535

- Caution
  - Indicates a potentially hazardous situation which, if not avoided, **<u>may result in minor or moderate injury</u>**. It may also be used to alert against unsafe practices that may cause property damage.
- Warning
  - Indicates a potentially hazardous situation which, if not avoided, **<u>could result in death or serious injury</u>**. This signal word should not be used for property damage hazards unless personal injury risk appropriate to this level is also involved.
- Danger
  - Indicates an imminently hazardous situation which, if not avoided, **<u>will result in death or serious injury</u>**. This signal word is to be limited to the most extreme situations. This signal word should not be used for property damage hazards unless personal injury risk appropriate to this level is also involved.

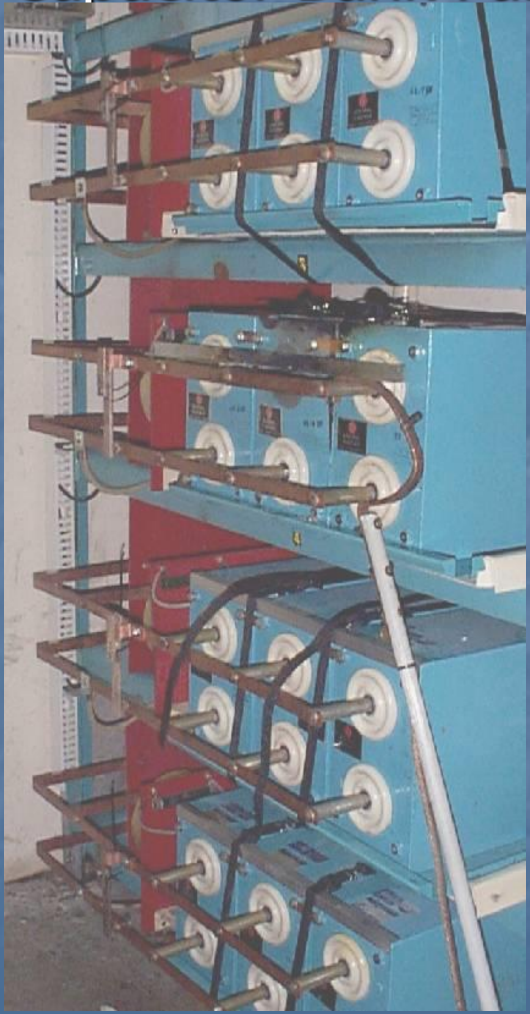


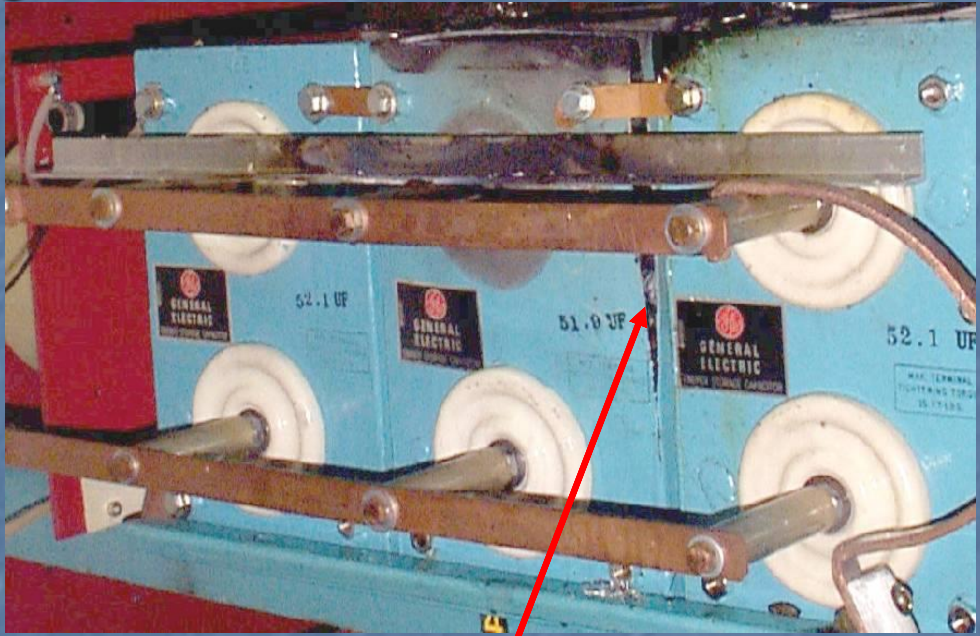




Enclosure – Cap Bank Exclusion Area

- Capacitor Bank Failure

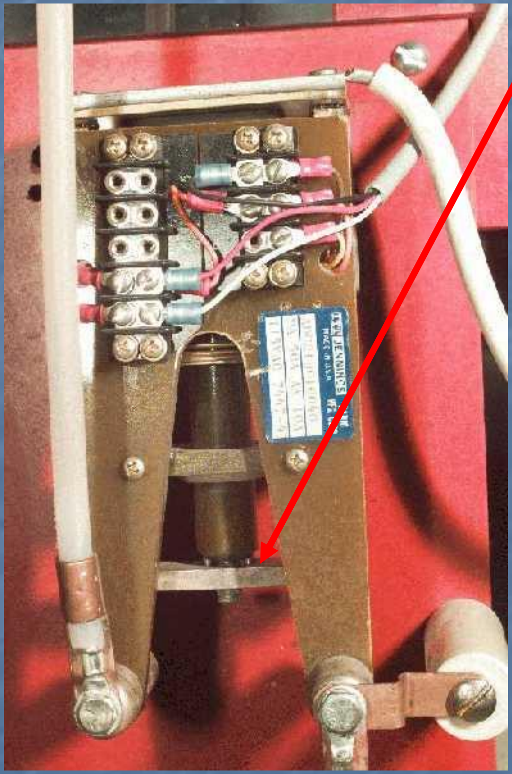




Case has split wide open, but cap is still connected

Enclosure – Dumps must be Observable

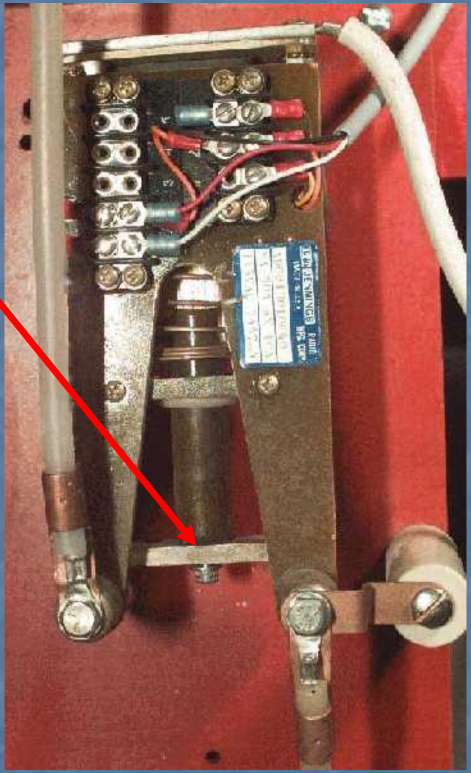
- Failed Dump Relay - no Bleeders on Cap



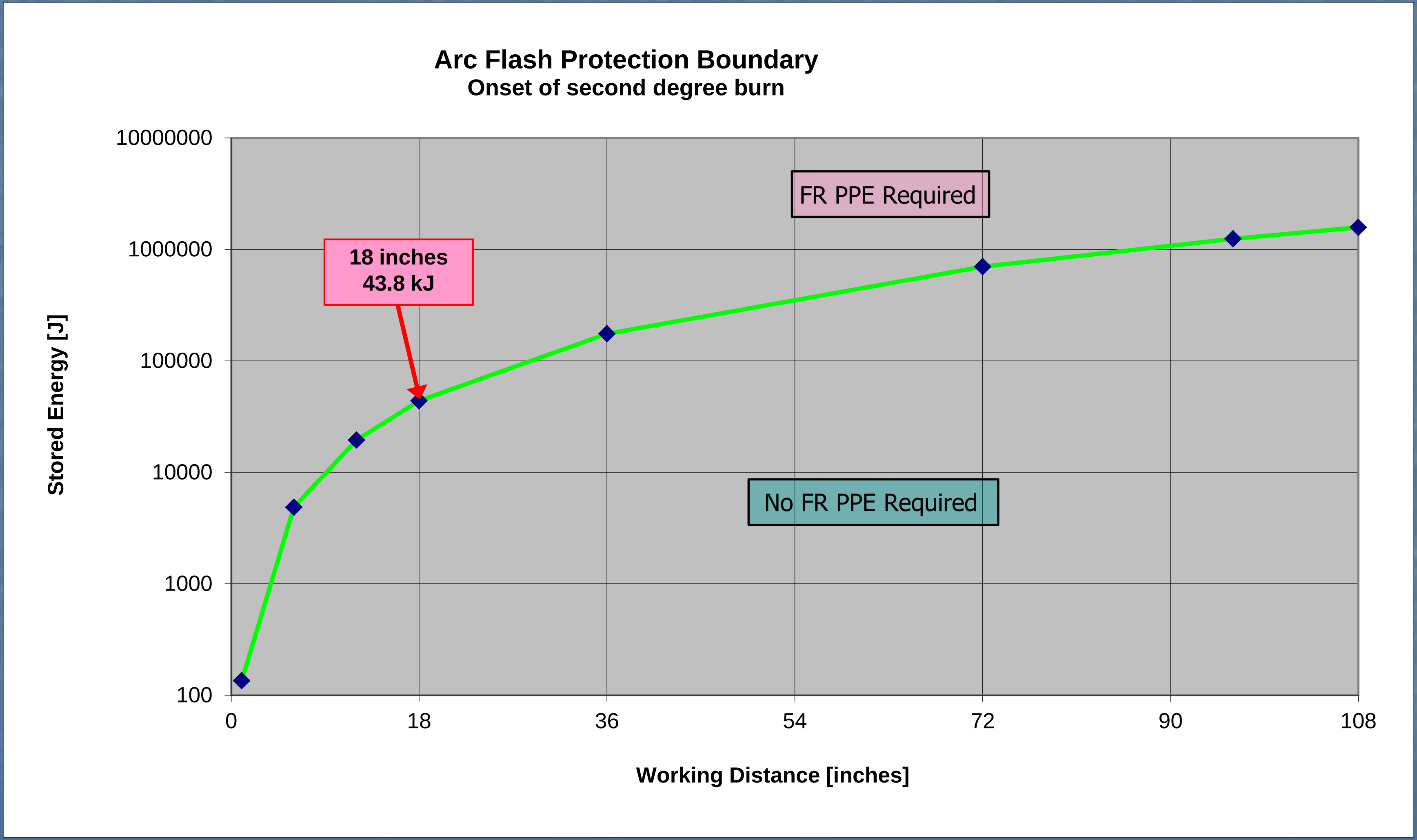
BAD

To Stick or not to Stick

GOOD



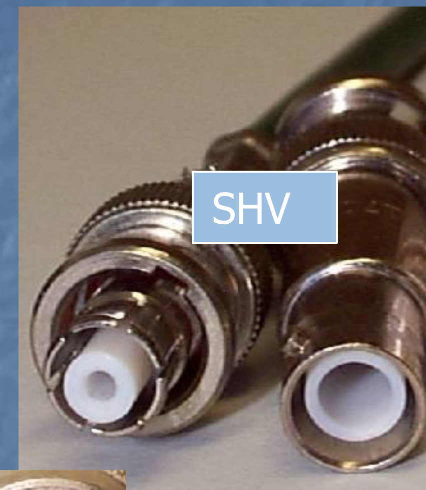
Flash Protection Boundary R&D
Capacitor Banks



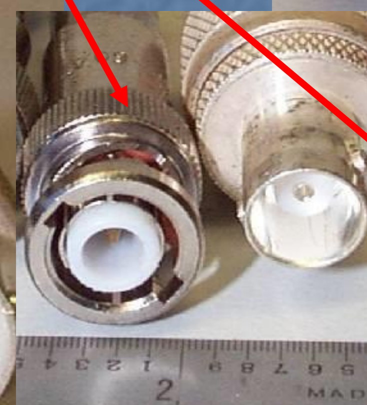
Enclosure – External Connectors must be Guarded

- 10 kV Chassis Connector Nightmare
- SHV MHV C

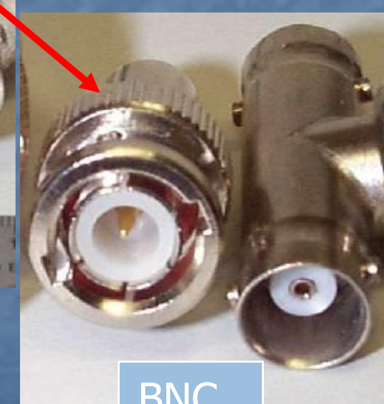
50 Volts or less since MHV and BNC connectors mate easily



SHV



MHV



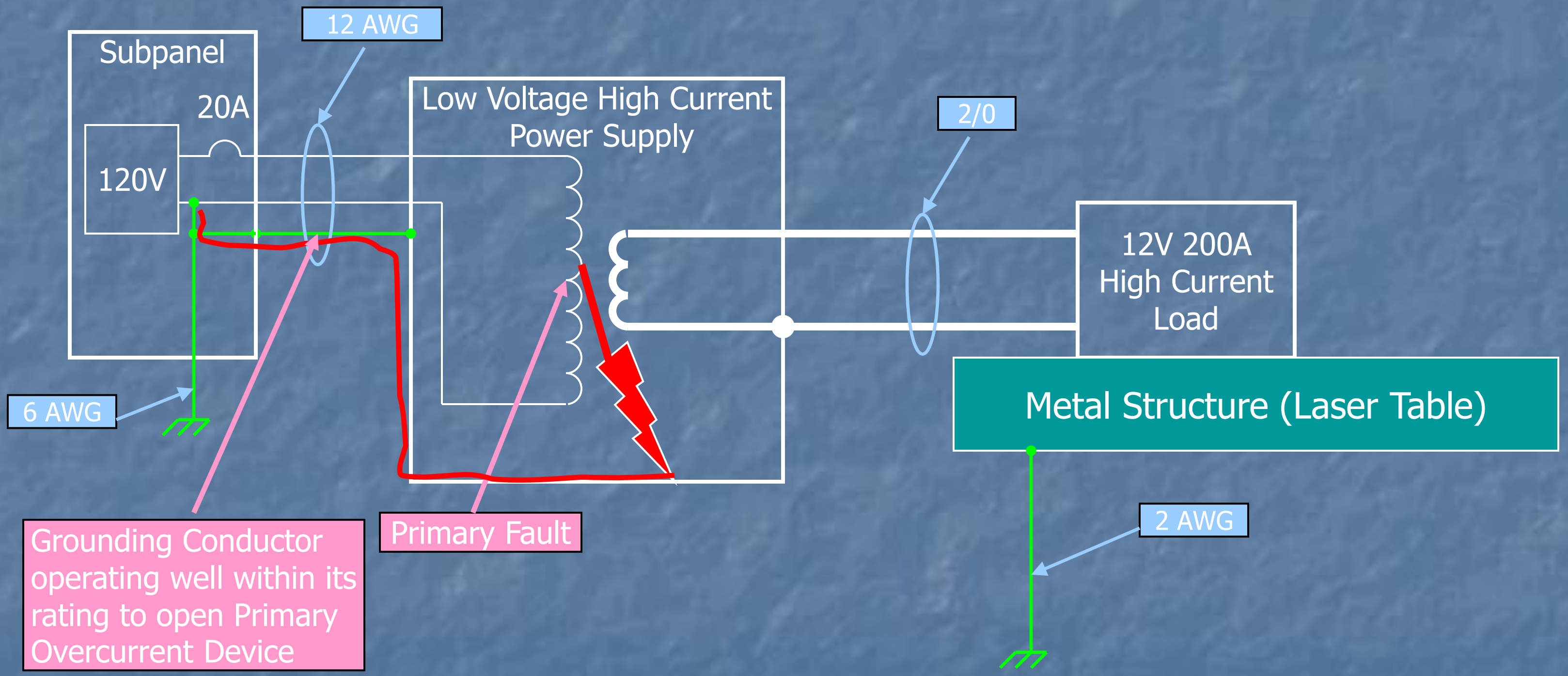
BNC

R&D HC Grounding & Bonding

- NEC is deficient for Pulse Power and Transformer Isolated Current-limited Loads
  - Specifies grounding conductor size to cause primary overload to open during primary fault only
    - Usual fault is primary insulation failure
  - Primary overcurrents are not necessary during secondary faults
    - Overloads will not open
    - Primary circuit is operating within normal current levels
  - Normal large load currents will damage equipment grounding conductor
    - Must only exceed the I^2T rating of the conductor to cause melting
    - Must only exceed the insulation temperature rating (90 degC) to cause a fault
    - Can be DC or pulsed current

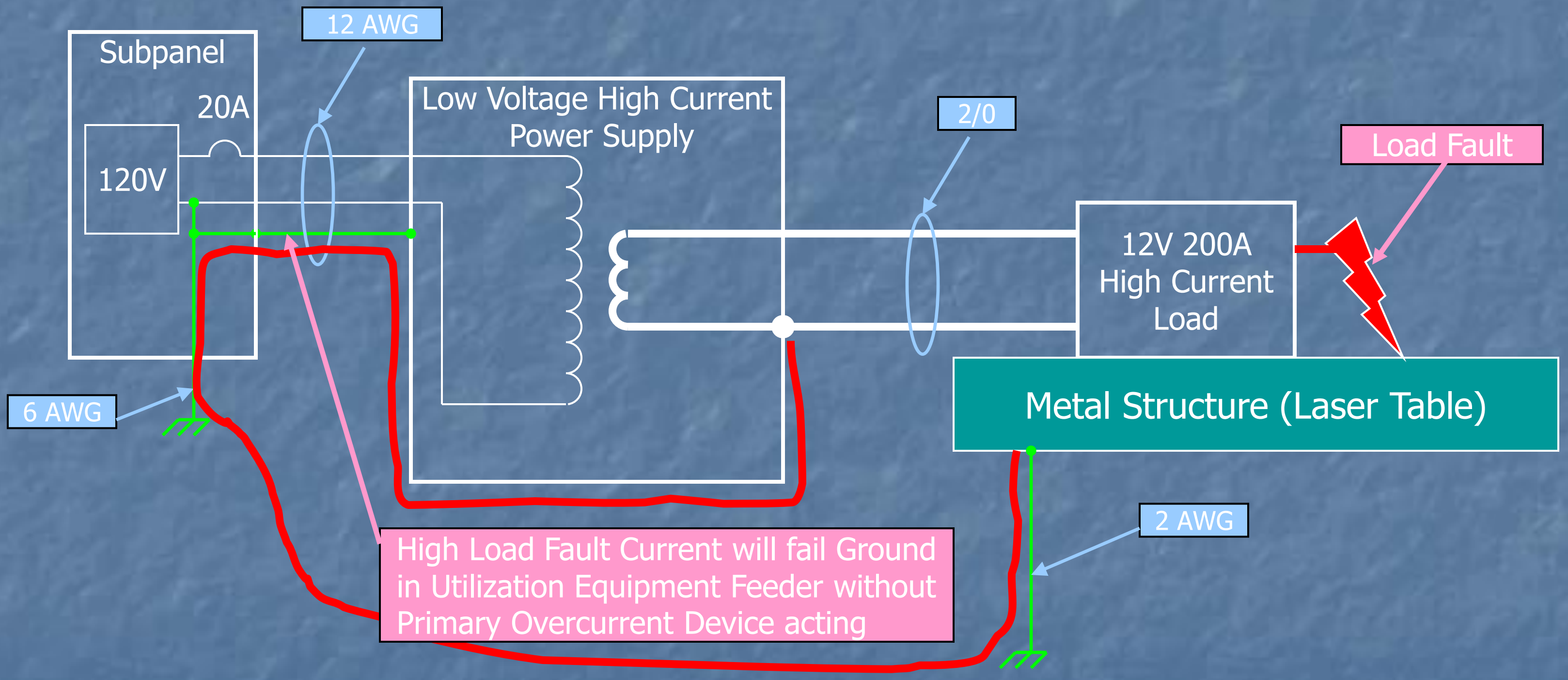
R&D HC Grounding & Bonding

- NEC – solves primary fault to case



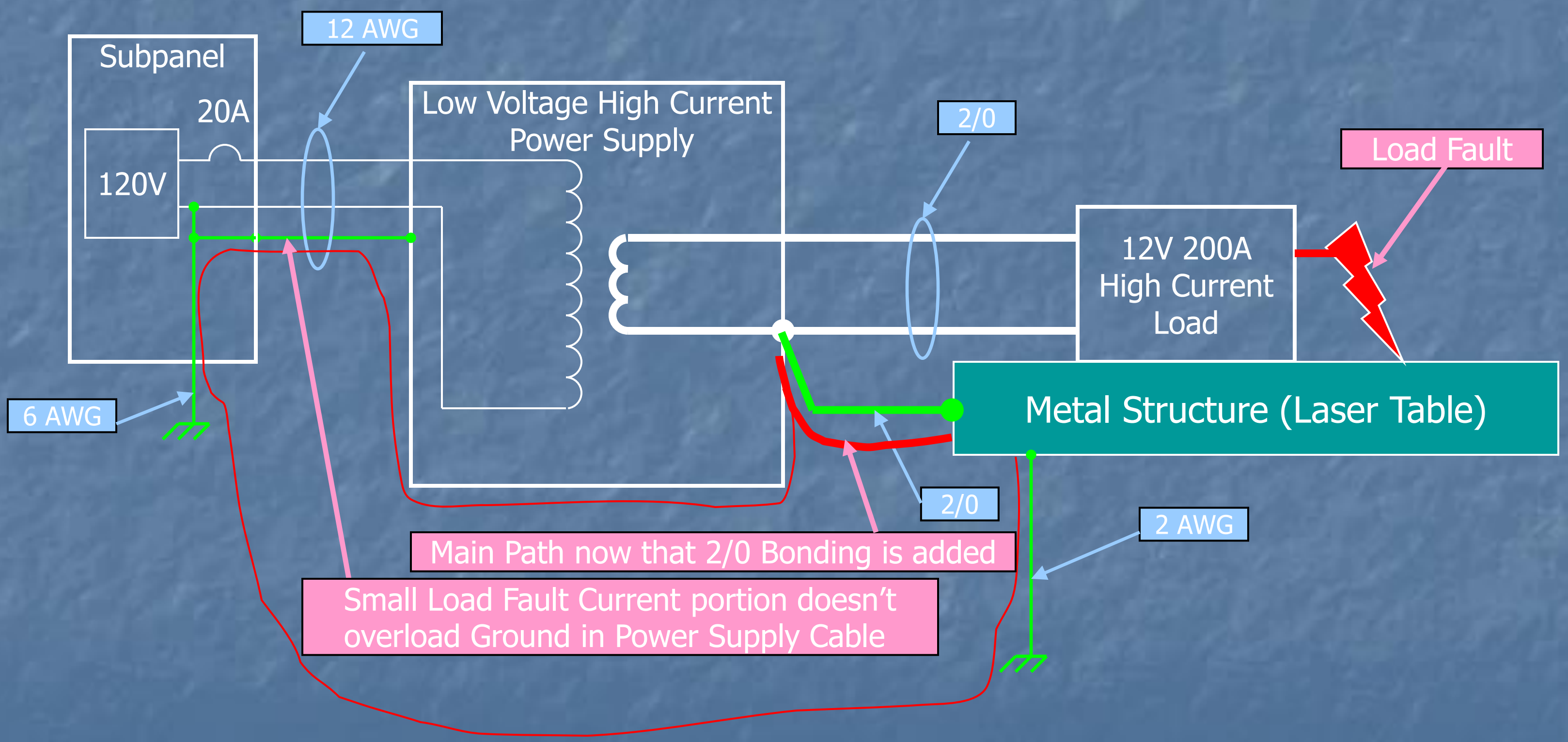
R&D HC Grounding & Bonding

- Problem when fault is to table from PS output



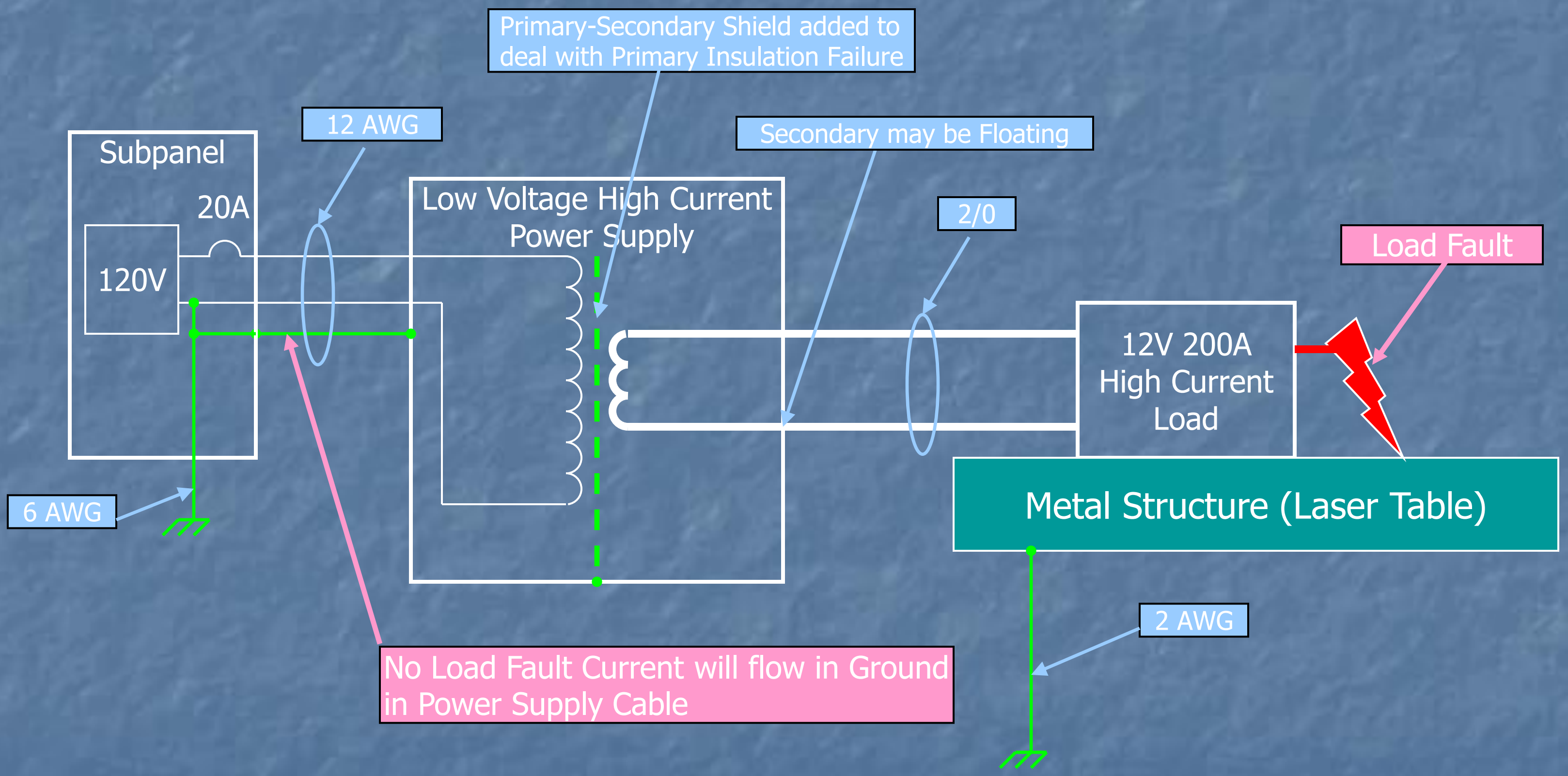
R&D HC Grounding & Bonding

- Solution 1 – Bonding of Load to PS



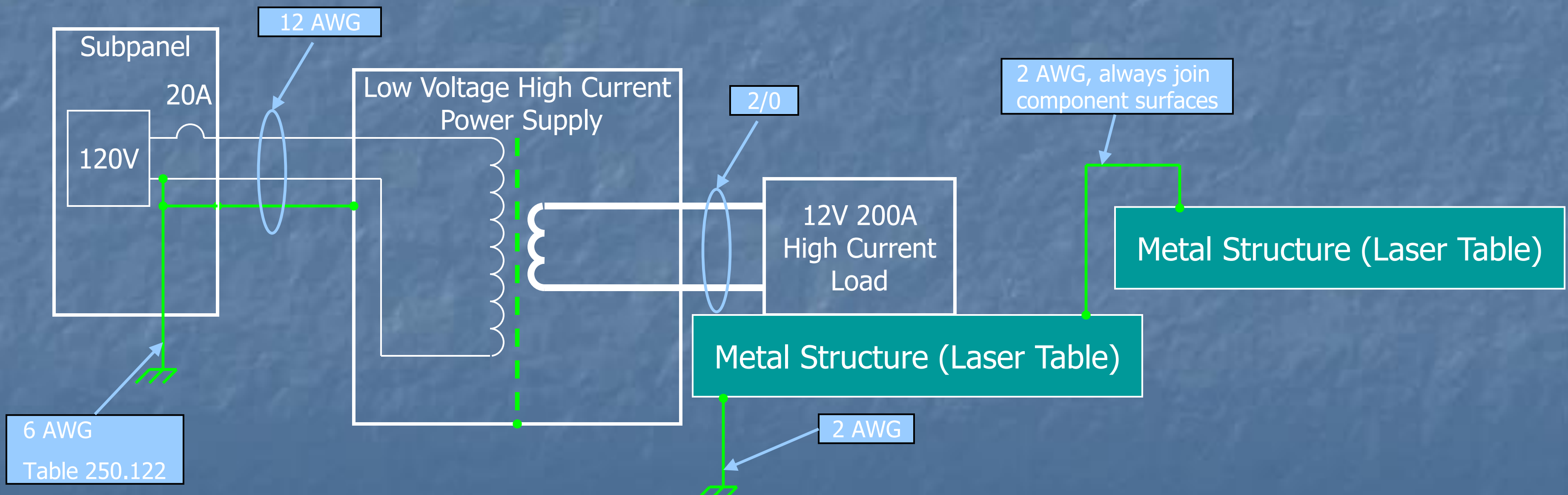
R&D HC Grounding & Bonding

- Solution 2 – Transformer Inter-winding Shield allows secondary to float



R&D HC Grounding & Bonding

- How do you bond additional Laser Tables?
  - For the AC standard hazard (branch circuits fed by a power panel), size the bond from NEC Table 250.122
  - For Pulse Power or HC power supplies, bond using the full-rated conductor from NEC 310.15(B)(16)
    - LLNL uses 2 AWG or 1”x1/16” copper strap for bonding at a minimum or under engineering supervision for small tables.



Grounding & Bonding

- Most confuse Bonding with Grounding. Almost all connections in the electrical world are actually bonds. From the NEC:
  - Bonding - The permanent joining of metallic parts to form an electrically conductive path that ensures electrical continuity and the capacity to conduct safely any current likely to be imposed.
    - The purpose of bonding is to establish an effective path for fault current that, in turn, facilitates the operation of the overcurrent protective device.
  - When you use water cooling of laser components, the water piping and tubing must be considered as a possible electrical conductor. The bonding is usually accomplished by passing the water supply and return through a metallic element that is bonded to the enclosure frame.

Bonding Failures (by Design)

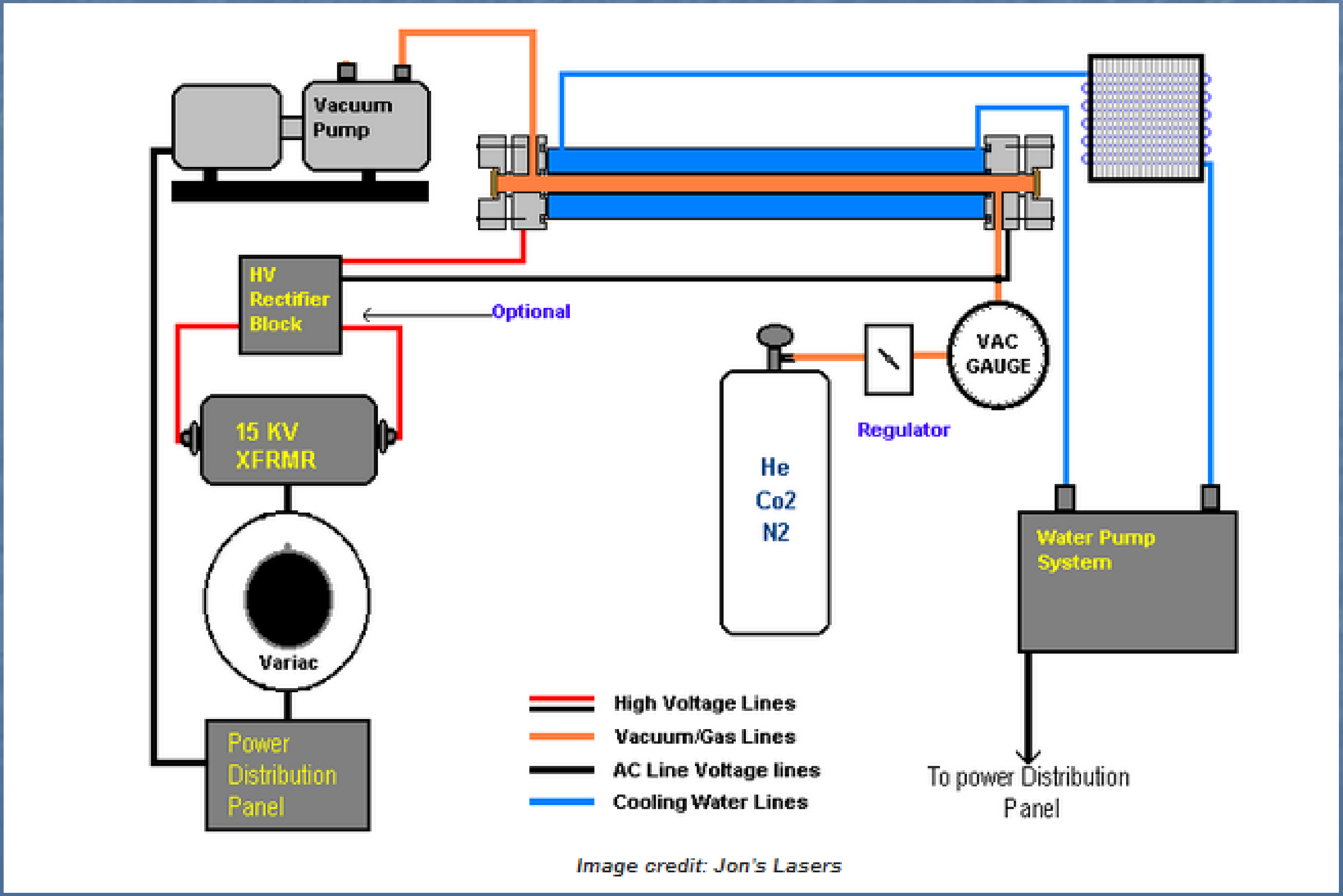
- Anodized surfaces are not valid bonding connections.
- Aluminum that is treated with irridite or alodyne process (MIL-C-5541E, class 3, color golden) can be treated as a conductor when bolted together. Otherwise the natural oxidation process makes an unreliable connection.
- Door hinges are never a valid electrical bond.
- Sheet metal fasteners are not allowed.
- Painted surfaces require stripping or special penetrating washers.

Bonding Failure for Water Cooling

- A concentric cooling jacket on a glass laser tube became energized due to a gasket failure.
- The tube filled partially with water and the laser continued to operate until the low water level sensor tripped the interlocks.
- During that time, the cooling hoses to the external chiller were energized at the anode potential.

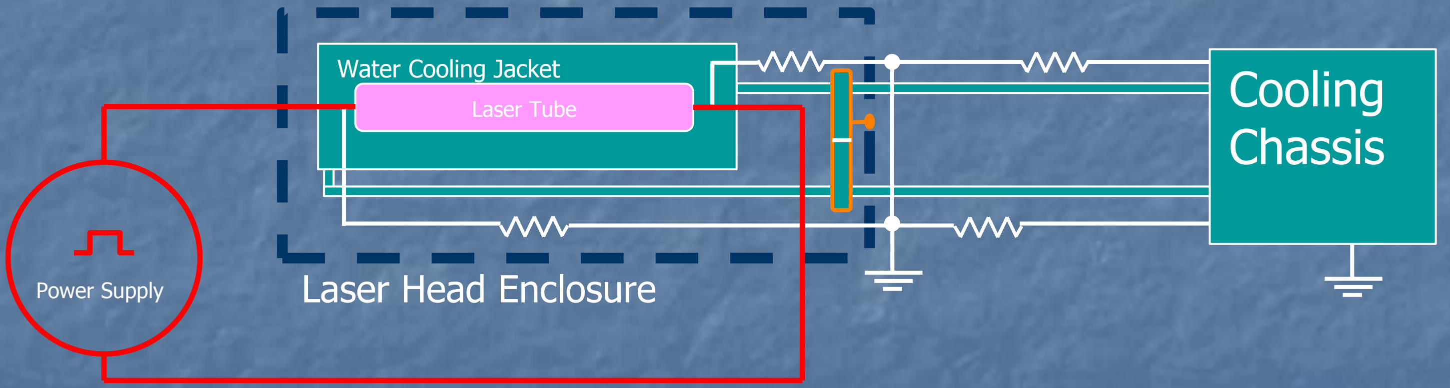
Bonding Failure for Water Cooling, p2

- Sketch for system layout of a typical CO2 laser



Bonding Failure for Water Cooling, p3

- Water becomes a distributed resistor grid, which must be bonded to the grounded frame of the laser head enclosure.
  - Laser tube has a breakdown to the cooling jacket
  - Water hoses now are at the HV of the tube
  - Constructing the enclosure with bonding feedthru connectors or a water manifold eliminates the shock risk



Effects of Electrical Energy on Man

Effects of Electric Current on Man [mA], Dalziel 1961						
	DC, see note		60 Hz		10 kHz	
Effect	Men	Women	Men	Women	Men	Women
Slight sensation	1	0.6	0.4	0.3	7	5
Perception	5.2	3.5	1.1	0.7	12	8
Shock-not painful	9	6	1.8	1.2	17	11
Painful Shock	62	41	9	6	55	37
Painful, Let-go Threshold	76	51	16	10.5	75	50
Painful, Breathing Difficult	90	60	23	15	94	63
Possible Ventricular Fibrillation						
3 sec shock	500	500	100	100		
Short Shocks for T seconds			165/sqrt(T)	165/sqrt(T)		
HV surges	50J	50J	13.6J	13.6J		

Note for DC tests: Tests using gradually increasing direct current produce sensations of internal heating rather than severe muscular contractions. Sudden changes in the current magnitude produce powerful muscular contractions, and interruption of the current always produces a very severe shock. The muscular reactions when the test electrode was released at the higher values were objectionable and sooner or later all subjects declined to attempt higher currents.

Let Go Currents

FIGURE 1. Let-go-current distribution curves for men and women (at 60-Hz commercial alternating current).

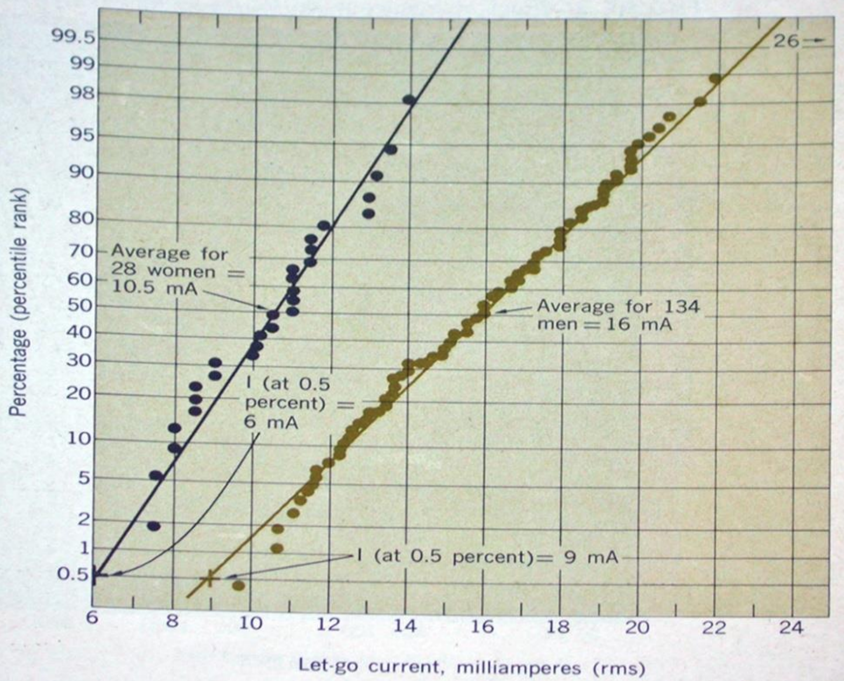
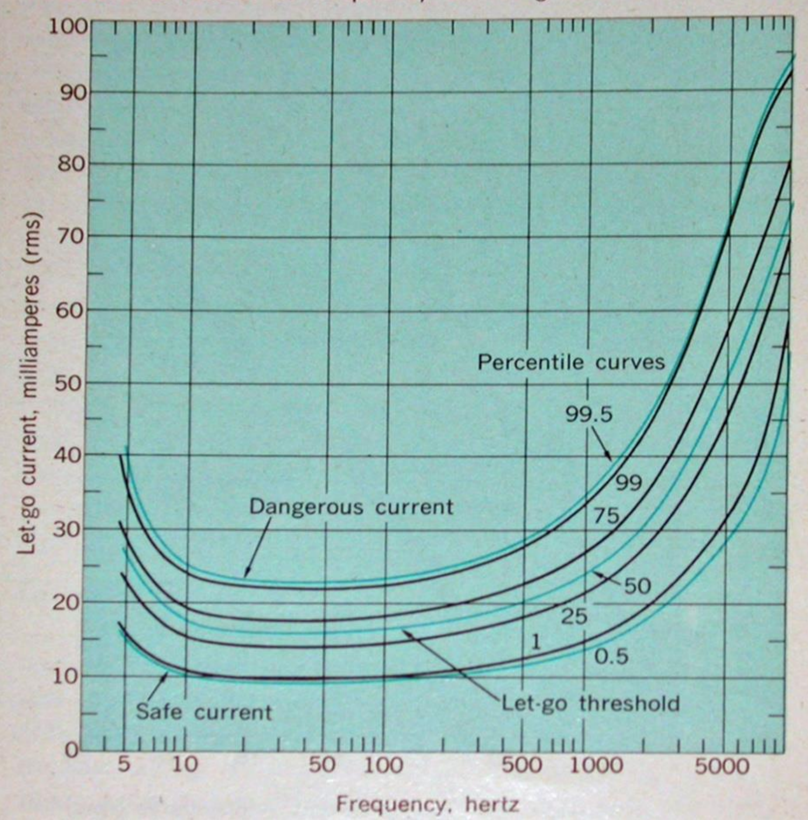
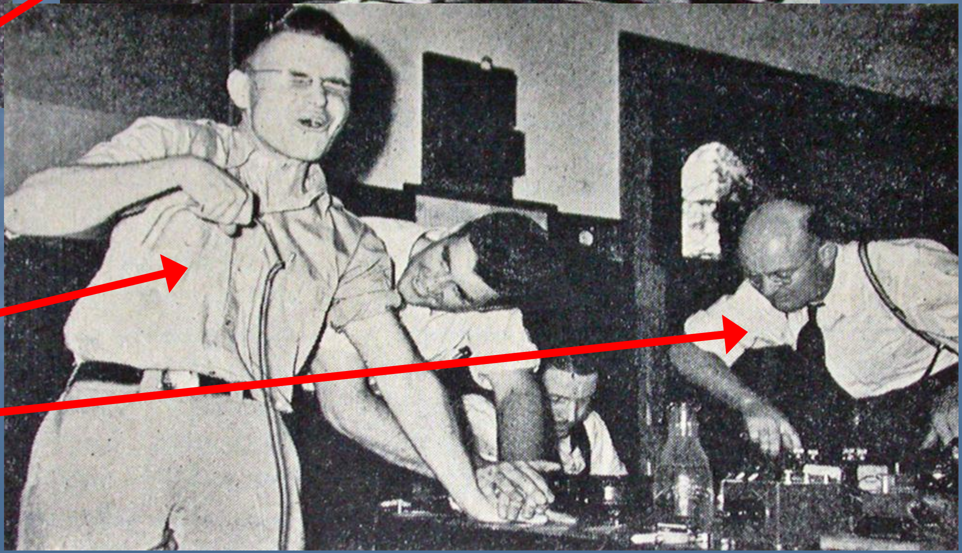


FIGURE 2. Effect of frequency on let-go-current for men.

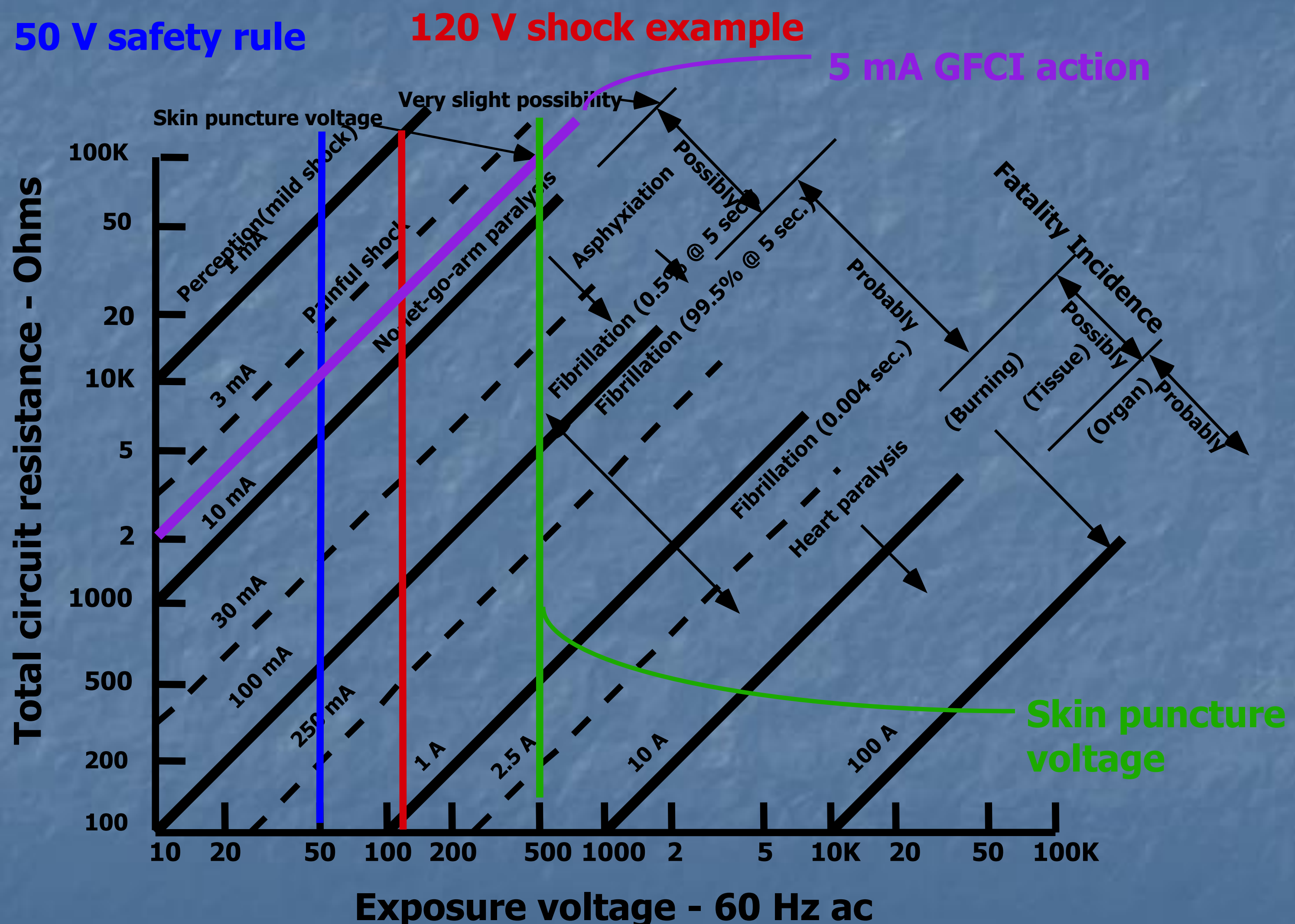


Measuring the Let Go Currents



- Let Go of 12 mA
- Let Go of 17.6mA
- 2mA above Let Go
- Dalziel getting data

Worker Electrical Hazards



Electrical Hazard – AC Shock

5.1 APPROACH BOUNDARY ANALYSIS FOR 60 HZ AC

Approach boundary analysis (including the determination of the Limited, Restricted, and Prohibited Shock Boundaries) is based on the phase-to-phase voltage of the exposed conductor. Approach boundary tables are found in NFPA 70E for 60 Hz AC. Table D-4 is taken from NFPA 70E, Table 130.2(C).

(1)	(2)	(3)	(4)	(5)
	Limited Approach Boundary			
Nominal System Voltage Range, Phase-to-Phase	Exposed Movable Conductor	Exposed Fixed Circuit Part	Restricted Approach Boundary, Includes Inadvertent Movement Adder	Prohibited Approach Boundary
≤50	Not specified	Not specified	Not specified	Not specified
50–300	3.05 m (10'0")	1.07 m (3'6")	Avoid contact	Avoid contact
301–750	3.05 m (10'0")	1.07 m (3'6")	304.8 mm (1'0")	25.4 mm (0'1")
751–15 kV	3.05 m (10'0")	1.53 m (5'0")	660,4 mm (2'2")	178.8 mm (0'7")
15.1–36 kV	3.05 m (10'0")	1.83 m (6'0")	787.4 mm (2'7")	254 mm (0'10")
36.1–46 kV	3.05 m (10'0")	2.44 m (8'0")	838.2 mm (2'9")	431.8 mm (1'5")
46.1–72.5 kV	3.05 m (10'0")	2.44 m (8'0")	1.0 m (3'3")	660 mm (2'2")
72.6–121 kV	3.25 m (10'8")	2.44 m (8'0")	1.29 m (3'4")	838 mm (2'9")
138–145 kV	3.36 m (11'0")	3.05 m (10'0")	1.15 m (3'10")	1.02 m (3'4")
161–169 kV	3.56 m (11'8")	3.56 m (11'8")	1.29 m (4'3")	1.14 m (3'9")
230–242 kV	3.97 m (13'0")	3.97 m (13'0")	1.71 m (5'8")	1.57 m (5'2")
345–362 kV	4.68 m (15'4")	4.68 m (15'4")	2.77 m (9'2")	2.79 m (8'8")
500–550 kV	5.8 m (19'0")	5.8 m (19'0")	3.61 m (11'10")	3.54 m (11'4")
765–800 kV	7.24 m (23'9")	7.24 m (23'9")	4.84 m (15'11")	4.7 m (15'5")

Electrical Hazard – DC Shock

5.2 APPROACH BOUNDARY ANALYSIS FOR DC

(1) Nominal Voltage Conductor to Ground	(3) Limited Approach Boundary Exposed Fixed Circuit Part	(4) Restricted Approach Boundary, Includes Inadvertent Movement Adder	(5) Prohibited Approach Boundary
≤100	Not specified	Not specified	Not specified
100–300	1.07 m (3’6”)	Avoid contact	Avoid contact
300–1000 V	1.07 m (3’6”)	304.8 mm (1’0”)	25.4 mm (0’1”)
1–5 kV	1.53 m (5’0”)	450 mm (1’7”)	100 mm (0’4”)
5–15 kV	1.53 m (5’0”)	660.4 mm (2’2”)	178.8 mm (0’7”)
15 kV–45 kV	2.5 m (8’0”)	838.2 mm (2’9”)	431.8 mm (1’5”)
45 kV–75 kV	2.5 m (8’0”)	1 m (3’2”)	660.4 mm (2’2”)
75 kV–150 kV	3 m (10’0”)	1.2 m (4’0”)	1 m (3’2”)
150 kV–250 kV	4 m (11’8”)	1.7 m (5’8”)	1.6 m (5’2”)
250 kV–500 kV	6 m (20’0”)	3.6 m (11’10”)	3.5 m (11’4”)
500 kV–800 kV	8 m (26’0”)	5 m (16’5”)	5 m (16’5”)

Notes:

1. The symbol ‘ is used for feet and “ for inches. Thus, 3’6” means 3 feet, 6 inches.
2. All dimensions are distance from live parts to worker.
3. Voltage is conductor to ground.
4. Exposed Fixed Circuit Part means that the bare conductor or other circuit part is stationary and does not move.
5. The voltage ranges were simplified from NFPA 70E. Conservative values (e.g., the higher values) were chosen.
6. The distances were rounded up to generate simpler numbers.
7. Boundary numbers are ≤ and >. For example, ≤100 V is not a DC shock hazard, >100 V is a DC shock hazard.

Table D-5. Approach boundaries to energized electrical conductors or circuit parts for shock protection, DC.

Inside the Restricted Approach Boundary Energized PPE is Required

Class	Proof Test voltage AC/DC	Maximum Use Voltage AC/DC
00	2,500/10,000	500/750
0	5,000/20,000	1,000/1,500
1	10,000/40,000	7,500/11,250
2	20,000/50,000	17,000/25,500
3	30,000/60,000	26,500/39,750
4	40,000/70,000	36,000/54,000

LSO Electrical Safety Resources

- NFPA 70 and 70E
- OSHA
- 10CFR851
- DOE Electrical Safety Handbook – DOE-HDBK-1092-2013
- General Duty Clause - 29 USC 654
- List of NRTLs
- UL Online Certification Directory
- UL Catalog of Standards

50 Joule shock

- Following the advice in the preceding slides, you and your co-workers should never be exposed to a shock from your equipment.
- Just as a reminder, even small shocks are painful—here is a reminder

- Atrial Fib Treatment with a 50 Joule shock
- This is the energy that many of your smaller pulse lasers operate at.
  - Example – at 10 Hz that would be a 500W electrical pump